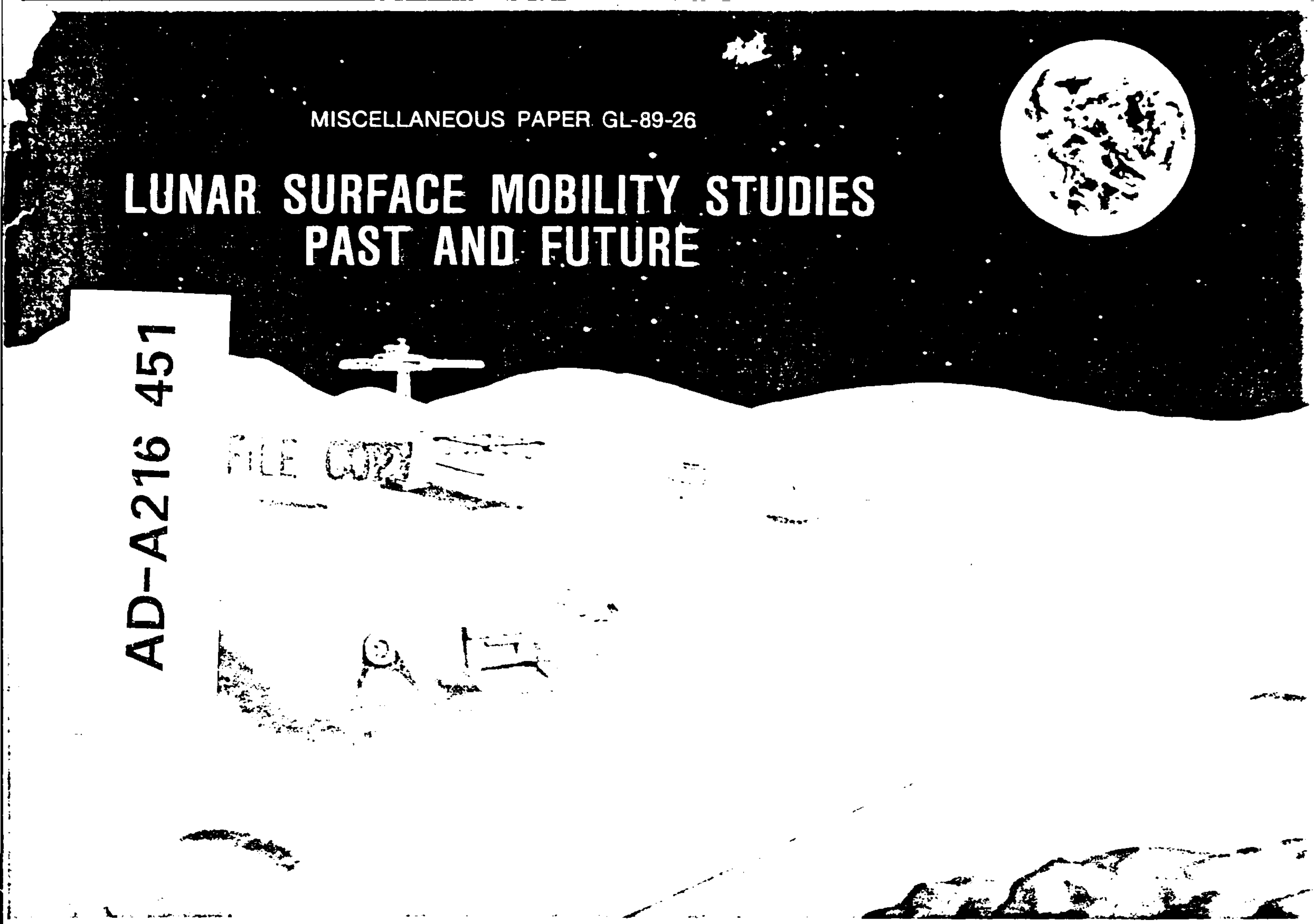
MISCELLANEOUS PAPER GL-89-26

LUNAR SURFACE MOBILITY STUDIES PAST AND FUTURE



by

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November 1989

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Civil Works Research Work Unit 31700

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): Miscellaneous Paper GL-89-26

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION: USAEWES Geotechnical Laboratory

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code): 3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: US Army Corps of Engineers

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code): Washington, DC 20314-1000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
			312-31700

11. TITLE (Include Security Classification): Lunar Surface Mobility Studies, Past and Future

12. PERSONAL AUTHOR(S): Turnage, Gerald W., Banks, Don C.

13a. TYPE OF REPORT: Final report

13b. TIME COVERED: FROM ________ TO ______

14. DATE OF REPORT (Year, Month, Day): November 1989

15. PAGE COUNT: 44

16. SUPPLEMENTARY NOTATION: Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Lunar mobility; Lunar soil simulates; Mobility models

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Prior to, during and shortly after the United States Apollo missions of some twenty years ago, WES was heavily involved under contract to NASA in conducting laboratory tests and analytical studies to define the mobility capabilities of proposed lunar surface vehicle concepts. Those WES efforts contributed to selection of the metal-elastic wheels successfully used on the Lunar Roving Vehicle (LRV) and, in association with efforts by the George C. Marshall Space Flight Center (MSFC), produced a quantitative description of the high-level mobility capabilities of a concept tracked running gear proposed for future US lunar surface applications (the Elastic Loop Mobility System, or ELMS). This paper reviews highlights of those Apollo-era studies--first, the determination and quantitative characterization of two terrestrial soils each successfully processed to provide a lunar soil simulant (LSS); then, the analysis of results from mobility tests conducted in LSS with several candidate LRV wheels and with several versions of the ELMS. The paper then describes capabilities developed since Apollo for use today in analyzing the mobility and

(Continued)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

20. ABSTRACT (Continued).

soil-working potential of future US LRV's. These capabilities include judicious application of soil-running gear dimensional analysis relations, plus the use of computerized models to be modified from terrestrial to lunar applications for predicting vehicle mobility and bulldozer working capability (e.g., the Army Mobility Model and the Push-It Model, respectively). Future studies of lunar surface vehicle mobility capabilities must profit from two major lessons learned from Apollo--i.e., how to process and quantitatively describe LSS, and to appreciate that physical testing in LSS of proposed running gears and vehicles is a necessary part of lunar vehicle mobility studies. Making use of these capabilities and lessons learned, and backed by national will, the United States is in far better position today than twenty years ago to develop outstanding capabilities for traveling on and working the surface of the Moon.

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SECURITY CLASSIFICATION OF THIS PAGE

PREFACE

In May 1961, President John F. Kennedy challenged the Nation with ... "achieving the goal, before the decade is out, of landing a man on the Moon and returning him safely to Earth" ... In April 1963, the Office of the Chief of Engineers, US Army Corps of Engineers completed a study commissioned by the National Aeronautics and Space Administration, entitled "Lunar Construction". This study, while dated, when revisited, still embodies many concepts of today's planning for Lunar habitation. The US Army Engineer Waterways Experiment Station responded later to the challenge by evaluating mobility capabilities of proposed lunar surface vehicles. In July 1989, in commemoration of the Apollo 11 landing, President George H. W. Bush said ... "And later this evening, after the crowd disperses and the sun goes down, a nearly full Moon will rise out of the darkness and shine on an America that is prosperous and at peace. And for those old enough to remember that historic night 20 years ago - step outside with your children or your grandchildren. Lift your eyes skyward and tell them of the flag - the American flag - that still flies proudly in the ancient lunar soil ... We had a challenge. We set a goal. And we achieved it ... (but) the time has come to look beyond brief encounters ... We must commit ourselves anew to a sustained program of ... permanent settlement of space ... And next - for the new century - back to the Moon. Back to the future. And for this time, back to stay."

The US Army Corps of Engineers' motto for over two centuries has been "Essayons" - "Let Us Try." During that time, the Corps has both tried and succeeded in meeting all important challenges for the Nation - one of the most important being that issued by President Kennedy. In anticipation of the Corps' role in meeting President Bush's challenge for lunar construction and habitation, a review was made of capabilities for quantatively describing lunar surface vehicle mobility based on studies conducted some 20 years ago and since by the US Army Engineer Waterways Experiment Station (WES). That review was prompted by a Call for Papers for Space '90 - an American Society of Civil Engineers Specialty Conference which in part, is cosponsered by the US Army Corps of Engineers. That review is the subject of this report.

The review was made by Mr. Gerald W. Turnage, Research Civil Engineer, Mobility Systems Division and by Dr. Don C. Banks, Chief, Soil and Rock Mechanics Divison, both employed in the Geotechnical Laboratory, WES. The cover drawing is by Charles C. Calais, Illustrator and the cover design is by Emily G. Mitchell, Visual Information Specialist, Visual Products Section, Information Technology Laboratory, WES. The Chief, Mobility Systems Division is Mr. Newell R. Murphy; the Chief, Geotechnical Laboratory is Dr. W. F. Marcuson III.

This report was prepared under the tenure of COL Larry B. Fulton, Commander and Director of WES; Dr. Robert W. Whalin is the Technical Director.

This work is endorsed by the Office, Chief of Engineers with acknowledgements by the Office, Strategic Initiatives and published with funds of the Civil Works Research and Development Program (Materials--Special Studies--Rock--Work Unit 312-31700).

Contents

CONVERSION FACTORS: METRIC (SI) TO NON-METRIC UNITS OF MEASUREMENT

Multiply	by	To Obtain
centimeters	0.3937	inches
centimeters	0.0328	feet
grams per cubic centimeter	62.43	pounds (mass) per cubic foot
kilopascals	0.1450	pounds (force) per square inch
meter-newtons	0.7375	foot-pounds (force)
meters per second	3.281	feet per second
meters per second	2.237	miles per hour
meganewtons per cubic meter	3.684	pounds (force) per cubic inch
megapascals per cubic meter	3.684	pounds (force) per cubic inch
millimeters	0.03937	inches
newtons	0.2248	pounds (force)
square centimeters	0.1550	square inches

LUNAR SURFACE MOBILITY STUDIES, PAST AND FUTURE

Introduction

In May 1961, President John F. Kennedy issued the challenge "of landing a man on the Moon and returning him safely to Earth...;" that challenge was realized with the July 1969 successful Apollo 11 mission. The United States over the next three years successfully placed men n the moon on five more occasions. Now some twenty years later, there is renewed national interest in returning to the Moon for exploration, scientific and industrial purposes.

For future travel on and working of the lunar surface, there must be assurance that the running gear selected will transport the lunar roving vehicle successfully. Thus, it is imperative to:

a. Review findings from mobility investigations conducted during the development and successful application of the wheeled LRV in the Apollo missions of twenty years ago.

b. Describe results obtained from testing and analyzing the mobility performance of a proposed tracked LRV (the ELMS).

c. Describe aspects of today's vehicle mobility analytical prediction capabilities useful for evaluating proposed future wheeled or tracked LRV's.

d. Propose a combination of analytical modeling and physical testing that makes use of both today's mobility modeling capabilities and lessons learned during Apollo. Use this solid basis to define LRVs that satisfy future U.S. needs for travel on and working of the lunar surface.

Lunar Surface Mobility Studies--A Review of Apollo-Era Findings

Background

From April 1969 to June 1974, the WES conducted a series of vehicle running gear mobility investigations under contract to the Lunar Exploration Office, National Aeronautics and Space Administration (NASA), and under the technical cognizance of the Space Sciences Laboratory, MFSC. These investigations involved physically testing within a laboratory environment a range of prototype vehicle running gears (first wheeled, later tracked), and analyzing the test results to recommend the best mobility characteristics for U.S. LRVs.

Simulation of lunar soil

A basic requirement of the WES investigations was to assure that pertinent properties of the soil(s) used for laboratory testing closely approximated those of lunar soil within the top 30 cm or so of the lunar surface. Two soil types were used during the WES investigations: a fine sand from the desert near Yuma, Arizona and a crushed basalt. The Yuma sand had a natural grain size distribution similar to that of lunar samples collected during the Apollo 11 and 12 missions (Melzer, 1974). The basalt was processed to a gradation similar to that of the lunar samples, and hereafter is referred to as lunar soil simulant (LSS). Figure 1 shows that gradations of the Yuma sand and the LSS closely matched the band of gradations for lunar core samples taken during Apollo 11 and 12.

For the laboratory testing of prototype lunar wheels, five levels of strength were used for Yuma sand (termed S_1, S_2, C_1, C_2 and C_3), and five for LSS (termed LSS_1 through LSS_5). During these two soils' use, each of their ranges of cohesive and frictional properties spanned a range believed to include the range of lunar soil properties.

To thoroughly characterize the properties of the Yuma sand, a range of types of laboratory soil tests were conducted, including: triaxial compression tests (conventional and vacuum), plain strain tests, direct shear tests, plate in situ shear tests, trenching tests, density and moisture content measurements (gravinimetric and nuclear methods), cone penetration tests, plus several special types of soil tests--Cohron sheargraph, vane shear, and Bevameter plate penetration and ring shear tests (Freitag, Green and Melzer, 1970). Somewhat fewer types of tests (taken from those just mentioned) were used to characterize the LSS.

For vehicle mobility considerations, the strength characteristics of primary interest were angle of internal friction, cohesion, and penetration resistance. To measure these characteristics, the soil tests determined most appropriate were the vacuum triaxial test, trenching test, and cone penetration resistance test, respectively. Figures 2, 3, and 4 show results of applying these tests for LSS (Melzer, 1974).

The conventional triaxial test, in which confining pressure is applied to a fluid surrounding the specimen, could not be used in testing LSS because of the low confining pressures under consideration. A series of vacuum triaxial tests was conducted at constant confining pressures of 3.5, 6.9 and 20.7 kPa, respectively. Figure 2 shows that a separate relation was defined among angle of internal friction, relative density and dry density for each confining pressure; this resulted because confining pressure, and thus normal stress, influenced the test results.

To evaluate the small amount of cohesion indicated present in lunar soil from experiences during Apollo 11, 12 and 14, a "trenching test technique" was conducted similar to that used on the lunar surface during the Surveyor program (Scott and Roberson, 1968). Lunar soil cohesion was known to cover a range of about 0.3 to 3 kPa. Apparent cohesion (c_a) of the LSS was created for a range of soil strengths by moistening the LSS slightly and uniformly, then compacting it to each of several relative densities. For a given moisture content and relative density, a vertical trench (or wall) was carefully dug into the LSS by progressively scooping out LSS at the bottom of the wall until the wall failed. Figure 3 shows relations among apparent cohesion (c_a) and relative density (D_r) or dry density (ρ_d) for values of moisture content (w) of 0.9 and 1.8 percent. In Figure 3, c_a increases with increasing D_r or ρ_d for a given level of w; for a given value of D_r or ρ_d, c_a increases with increasing w.

Cone penetration resistance tests were used to assess the uniformity of each LSS test bed (composed of a layer of LSS approximately 1 m wide and 35 cm deep prepared within a steel soil bin approximately 8 m long). WES experience in preparing test beds of air-dry Yuma sand over a broad range of consistencies during tests of pneumatic tires for terrestrial applications had verified that cone penetration measurements provide a simple, repeatable means for assessing both soil test bed strength and uniformity. Further, (Melzer, 1971) had demonstrated that cone penetration measurements can be related successfully to the relative density and dry density of cohesionless soils.

The WES standard cone penetrometer (Figure 5) has a cone of 30 deg apex angle, a base diameter of 2.03 cm (base area 3.23 sq cm), and is mounted on a shaft of smaller diameter (1.59 cm) to reduce skin friction . The cone was used to penetrate the soil vertically at a constant speed of 0.03 m/sec. to a depth of about 35 cm. The cone penetrometer was mounted on a carriage that ran on rails above the soil bin, so that any point in the bin could be reached. Cone penetration resistance (q_c, the penetration resistance force of soil divided by the cone base area, kPa)* increased approximately linearly with soil depth for each strength level of Yuma sand and of LSS within the 4 to 19 cm depth range. Gradient, G (or slope) of the q_c versus soil depth relation defined within that soil depth range was used as the primary index of soil test strength (WES standard procedure in mobility research for lightly loaded wheels or tracks).

Figure 4 shows the semilogarithmic relation of G to D_r and ρ_d for samples of LSS processed at values of w of 0.8 and 1.8 percent. As in Figure 3, the ranges of D_r and w values in Figure 4 correspond to the range of apparent cohesion values of interest for simulating lunar soil. The relations in Figure 4 show that for a given value of D_r and ρ_d, soil moisture content w influences G only if D_r is less than about 70 percent (ρ_d <1.80 g/cm^3). For denser LSS, the relations merge, at least for practical purposes. The following tabulation shows approximate average values of G, w, D_r and ρ_d for the strength levels of Yuma sand and of LSS used by WES during Apollo-era laboratory mobility testing.

	Yuma Sand					LSS				
	S_1	S_2	C_1	C_2	C_3	LSS_1	LSS_2	LSS_3	LSS_4	LSS_5
G, MN/m^3	0.54	3.07	1.91	3.20	3.95	0.22	0.60	1.76	1.01	6.39
w, percent	0.5	0.5	1.1	1.4	1.8	0.9	0.9	0.9	1.8	1.9
D_r, percent	32	87	46	54	48	31	42	52	32	59
ρ_d, g/cm^3	1.49	1.64	1.47	1.48	1.46	1.52	1.58	1.66	1.52	1.71

Types of wheel and track tests

<u>Programmed increasing slip tests</u>. Most of the WES laboratory mobility tests were conducted on level soil surfaces of either Yuma sand or LSS. A single wheel (or track) was mounted in a dynamometer system instrumented to continuously measure wheel (or track) load, pull, torque, sinkage and speed, plus carriage speed. With carriage speed designated as actual speed V_a, and wheel (or track) speed as theoretical speed V_t, wheel (or track) slip is

* q_c has the same meaning as cone index, CI.

defined as $1 - V_a/V_t$. During a given test, V_t was held constant and V_a was slowed at a uniform rate from a starting value larger than V_t to zero, causing slip to range from a negative value at the start of a test to 100 percent slip (spinout) at the end.

To account for the moon's gravitational pull being only about one-sixth that of earth's, WES used very light wheel and track test loads. Figure 6 shows representative curve shapes for input torque and output pull versus slip from programmed increasing slip tests of a lightly loaded wheel (or track) operating in loose and in dense lunar soil simulant (either Yuma sand or LSS). In Figure 6, the towed point (T) is reached at zero input torque, and the self-propelled point (SP) at zero output pull.

A ramped slip test technique and a modified programmed increasing slip test technique were evaluated in (Melzer 1971) relative to the programmed increasing slip technique used in the bulk of the WES wheel tests for NASA (as previously described). All three techniques produced the same results for given sets of soil and wheel test conditions.

Some important wheel and track test conditions. Three performance conditions are particularly important as defined from a programmed increasing slip test:

a. Towed condition: corresponds to the performance of a non-powered wheel (or track).

b. Self-propelled condition: corresponds to the performance of a powered wheel (or track) traveling on level terrain.

c. 20 percent slip condition: is a nominal slip level slightly larger than that at which the rate of increase in both input torque and output pull of a lightly loaded wheel (or track) drastically diminishes.

Reasons for the 20 percent slip condition being important include:

a. Pull coefficient (pull P divided by wheel (or track) load W at 20 percent slip, P_{20}/W) corresponds approximately to the maximum slope that a powered wheel (or track) can climb in a steady-state condition before the power consumption rate becomes excessive (Freitag, Green and Melzer, 1970).

b. Pull at 20 percent represents the approximate maximum that can be obtained before the wheel (or track) quickly spins out.

c. Sinkage of a wheel (or track) increases substantially beyond 20 percent slip compared to sinkage at 20 percent slip. (For the light loads of the WES lunar mobility tests of wheels and tracks, sinkage was small in nearly all tests.)

d. 20 percent slip represents a threshold value concerning relations of power input required and system efficiency. These relations are described two paraagraphs below.

Other types of tests. In addition to in-soil programmed increasing slip tests of wheels and tracks, WES also conducted in-soil slope climbing tests (in which the desired slope for a given soil test bed was obtained by lifting one end of the steel test bin to a prescribed height by means of an overhead crane). Obstacle override and crevice crossing tests were conducted only with the proposed lunar tracks.

Dimensionless descriptors of running gear performance

Programmed increasing slip tests. For the towed, self-propelled and 20 percent slip conditions, a reasonably comprehensive description of the mobility performance of a wheel* in a frictional soil can be provided by several dimensionless performance terms, described as follows:

a. Towed condition: P_T/W, slip, z_T/d

b. Self-propelled condition: M_{SP}/Wr_e, slip, z_{SP}/d

c. 20 percent slip: P_{20}/W, M_{20}/Wr_e, $_{20}$, z_{20}/d

where P_T/W = towed force coefficient [i.e., towed force P_T (the amount of pull that must be added to cause the wheel to reach the self-propelled condition), divided by wheel load W].

z_Td, z_{SP}/d, z_{20}/d = sinkage coefficients (i.e., sinkage z divided by unloaded wheel diameter d) for the performance levels indicated.

M_{SP}/Wr_e, M_{20}/Wr_e = torque coefficients (i.e., input torque M divided by the product of load W and wheel effective radius r_e) for the self-propelled and 20 percent slip conditions. r_e is wheel rolling circumference measured on a hard surface divided by 2π, and is closely approximated by $d-\delta/2$ (where d has been defined previously and δ is the deflection of a wheel statically loaded on a rigid, level surface.)

PN_{SP}, PN_{20} = power number for the self-propelled and 20 percent slip conditions. $PN = M/[Wr_e(1-s)]$, where s is slip expressed as decimal (not as a percent).

$_{20}$ = wheel system efficiency at 20 percent slip = $PV_a/M\omega_{20}$, where ω is wheel rotational velocity (equals V_t/r_e). Thus $_{20} = [(Pr_e/M)(1-s)]_{20} = (Pr_e/M)_{20} \times 0.8 = (P_{20}/W + M_{20}/Wr_e) \times 0.8$.

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* In the remainder of this paper, "wheel" is used to describe both the metal-elastic wheels and the pneumatic tires that were included in the WES mobility testing for NASA, unless otherwise specified. Note, too, that dimensionless performance descriptors similar to those subsequently described for wheels also apply for tracks.

Note in extrapolating from the definition of η_{20} to any positive value of slip, η is defined as $P/W + M/[Wr_e(1-s)]$, or P/W + PN. Representative plots of PN versus P/W and of efficiency versus slip are shown in Figures 7a and 7b, respectively. The plot of P/W versus PN is particularly useful relative to lunar surface travel; it expresses the energy consumed per unit of travel distance per unit of wheel load relative to the pull (and slope climbing) ability of the wheel. For example, to obtain the wheel power consumption rate PCR in watt · hr/km for operation on a 10 percent slope, first read the value of PN at P/W = 0.10 in Figure 7a; then multiply by wheel load W (expressed in newtons) and by the fraction 1/3.6 . Expressed in equation form, this is PCR = (PN/3.6) x W , derived as follows:

PCR = PN x W. Then, dimensionally

PCR = PN x N x 1000 m/km x hr/3600 sec = 1000/3600 x(M · N/sec) x hr/km

Since PN is dimensionless and a watt is torque per unit of time (i.e., 1 watt = 1 M · N/sec), then

PCR = PN/3.6 x W, in units of watt · hr/km, or energy consumed/km.

Other types of tests. The primary descriptor of wheel performance for a slope climbing test is the angle of maximum slope climbable (ϕ_{max}). For obstacle override and crevasse crossing tests, the primary descriptors are maximum negotiable obstacle height (OH_{max}) and maximum negotiable crevasse width (CW_{max}), respectively. Note that to portray these performance descriptors in dimensionless terms, ϕ is already dimensionless and OH_{max} and CW_{max} can each be expressed relative to a characteristics wheel or track dimension, say, wheel diameter d or track hard surface contact length ℓ .

Rationale for wheeled concept

Compared to tracked vehicles, wheeled vehicles generally provide better high-speed mobility, involve less weight, offer less mechanical complexity, and include more efficient drive systems (Melzer and Trautwein, 1972). The latter three characteristics are important in extraterrestrial operations and were major reasons why NASA selected a wheeled vehicle concept for the first U.S. Lunar Roving Vehicle.

The test wheels and surrogate wheeled vehicles

The original single test wheels evaluated by WES for NASA were: the pneumatic (tire), the Bendix, the Boeing-General Motors (GM), the Grumman, and the Surveyor Lunar Rover Vehicle (SLRV) wheels, each as shown in Figure 8. Additionally, tests were conducted with a surrogate 4x4 vehicle (all wheels powered) mounted on the same size pneumatic wheels, and with a surrogate 6x6 vehicle mounted on the same size SLRV wheels. The following tabulation lists values of unloaded (undeflected) wheel diameter d and wheel section width b for the original test wheels and vehicles:

Wheel or Wheeled Vehicle	Wheel diameter d (cm)	Wheel width b (cm)
Pneumatic (wheel)	97.4	22.0
Boeing-GM wheel	101.6	25.4
Grumman wheel	108.0	--
SLRV wheel	47.9	21.6
4x4, pneumatic wheels	97.1 (avg)	21.9 (avg)
6x6, SLRV wheels	47.7 (avg)	21.6 (avg)

Test loads ranged from 67 to 670N for each of the original test wheels, from 133 to 667N for the 4x4, and from 98 to 142N for the 6x6. Modifications to the test wheels up to the time of selection of wheels for the LRV included: addition of grousers to the Bendix and Grumman wheels; roughening the surface and adding several types of fabric covers to the Boeing-GM wheel; and later removing 50 percent of the Boeing-GM wheel's outer wire structure and covering it with a roughened fabric. Overall in this phase of the program, mobility testing included three versions of the Bendix, two of the Grumman, and six of the Boeing-GM wheels.

Analysis of in-soil performance of test wheels and surrogate wheeled vehicles

Method of analysis. One purpose of the test program was to study the relative effects on in-soil wheel performance of varying wheel dimensions, deflection characteristics, and loads. A dimensionless wheel-soil term (numeric) useful in predicting terrestrial pneumatic tire performance in Yuma sand had been reported by (Freitag, 1965) and by (Green, 1967), defined as follows:

$$N_{PY} = [G8bd)^{3/2}/W] \quad (\delta/h)$$

where h is tire undeflected section height, all other terms on the right have been previously defined, and PY indicates that N_{PY} is applicable for pneumatic tires operating in Yuma sand. For the WES mobility investigation of wheels relative to the LRV, a numeric was needed that excluded the dimension h so that the numeric could be related not only to pneumatic tires but also to rigid and metal-elastic wheels. The numeric determined best for this application took the form:

$$N_{WY} = (Gbd^2/W) \cdot [1 - (2\delta/d)]^{-8}$$

where all terms on the right have been previously defined and WY indicates that N_{WY} is applicable for wheels (pneumatic or otherwise) operating in Yuma sand.

From extensive mobility testing of pneumatic tires in air-dry Yuma sand conducted by WES prior to the mobility investigations for NASA, it had been determined that the maximum value of N_{WY} for ordinary terrestrial applications is somewhat less than 2000. The shape of the solid portion of the P_{20}/W versus N_{WY} curve in both Figures 9a and 9b was defined by those earlier test results; the curve was extended horizontally in (Freitag, Green and Melzer, 1970) for values of N_{WY} beyond about 2000. As shown in both Figures 9a and 9b, most of the P_{20}/W versus N_{WY} test results for the original and the modified candidate LRV wheels took values of N_{WY} much larger than 2000. Comparing Figures 9a and 9b, it is seen that, relative to the level of performance of the pneumatic tire (i.e., relative to the curve in each of Figures 9a and 9b): the original Bendix I wheel performed at about the same level; the modified Bendix II and III at somewhat higher levels; the Boeing-GM I at a considerably lower level, the Boeing-GM II through VI at somewhat improved through still lower levels; the Grumman I at the lowest level, the Grumman II at about the same level; and the SLRV at a slightly lower level.

(Freitag, Green and Melzer, 1970) also examined results from the same tests depicted in Figure 9 in terms of P_{20}/W versus $(G/W) \cdot A_c^{3/2}$, where A_c = contact area of the test wheel measured on a hard surface. (Freitag, Green and Melzer, 1970) noted that "Of the two functional relations...(i.e., P_{20}/W versus N_{WY} and P_{20}/W versus $(G/W) \cdot A_c^{3/2}$), the first ... is preferred because it gives the analyst a clearer picture of the relative effects on performance of altering wheel geometry and rigidity." Nevertheless, N_{WY} was not used again (nor was $(G/W) \cdot A_c^{3/2}$) in any of the subsequent analysis of the performance of the candidate LRV wheels in either Yuma sand or LSS. This decision may have been reached because (a) curves of N_{WY} versus most of the dimensionless in-soil wheel performance terms described earlier herein were relatively flat for N_{WY} values larger than about 2000, and/or (b) plots like those in either Figure 9a or 9b are confusing to interpret when data trends for several wheels are depicted only in terms of data points.

In any case, the major advantage of depicting in-soil wheel performance on a continuum--i.e., of describing performance in terms of dimensionless wheel performance coefficients versus a range of values of N_{WY}, where each value of N_{WY} corresponds to any combination (within reason) of input values of the soil and wheel test control variables G, b, d, W and δ which produces that particular N_{WY} value--was largely abandoned. Instead, each of a number of variables that had potentially major influence on in-soil wheel performance was evaluated in "snapshot" fashion--i.e., by systematically changing over a reasonably broad range the values of the variable being evaluated (say, wheel speed) while also systematically changing the values of one or more of G, b, d, W, and δ. Major results of those evaluations are described in approximate chronological order in the following paragraphs.

<u>Results from (Freitag, Green and Melzer, March 1970 and May 1970)</u>. These two reports describe results of tests in Yuma sand of the candidate single wheels proposed for the LRV, and of the 6x6 and 4x4 surrogate wheeled vehicles. Major findings obtained were:

<u>a</u>. <u>Effect of light loads</u>. For values of wheel load W less than 220N (50 lb), tests of the pneumatic and Bendix I wheels in air-dry Yuma sand showed that the P_{20} (ordinate) versus W (abscissa) relation is a straight line through the origin, with P_{20}/W having its maximum value within this region of values of W . For larger values of W, the relation starts to curve downward. From results of a particular test of a 9.00-14 pneumatic tire conducted in air-dry Yuma sand in a previous study (Green, 1967), it was demonstrated that as values of W are progressively increased, the relation of P_{20} to W followed the pattern shown in Figure 10. (In (Turnage, 1972) the general relation of P_{20} to W was developed from the relation of P_{20}/W to N_{PY} for pneumatic tires; this relation follows a pattern similar to that in Figure 10.)

<u>b</u>. <u>Effect of soil strength (cohesion)</u>. From (Freitag, Green and Melzer, May 1970) "Contrary to expectations, increases in cohesion did not result in a marked improvement in performance over the range of loads and soil conditions used in this study." (Loads of the single wheels in the study ranged from 67 to 670 N, conditions of the test soils were S_1, S_2, C_1, C_2 and C_3 as defined earlier herein.) For the five original test wheels, (Freitag, Green and Melzer, May 1970) described performance as follows:

Wheel	Soil Condition S_1 P_{20}/W*	PN_{SP}*	Soil Condition C_1 P_{20}/W*	PN_{SP}*
Pneumatic	0.448	0.150	0.548	0.040
Bendix I	0.452	0.067	0.505	0.080
SLRV	0.426	0.080	0.602	0.165
Boeing-GM I	0.274	0.098	0.343	0.067
Grummand I	0.281	0.162	0.272	0.127

* These data were averaged for the range of loads tested.

Power consumption rates for soil condition S_1 for the Bendix I, Boeing-GM I, and Grumman I wheels computed from their respective values of PN_{SP} and a procedure described in (Freitag, Green and Melzer, May 1970) were 4, 6 and 10 watt-hr/km, respectively.

c. Effect of wheel deflection. Tests of the pneumatic and the Bendix I wheels in Yuma sand condition S_1 at load deflections from about 10 to 22.5 percent caused little change in values of P_{20}/W. Decreasing deflection of the Boeing-GM wheels from 11.9 to 4.6 percent caused P_{20}/W to decrease noticeably in Yuma sand conditions S_1 and S_2. The conclusion was drawn that for a given wheel-soil condition, there is a limit beyond which a decrease in deflection leads to a decrease in wheel performance.

d. Effect of wheel contact pressure. P_{20}/W was found to be "independent of average contact pressure at the interface for pressures ranging from 0.7 to 3.5 kN/m^2 for a given soil condition. On the soils with the larger amounts of cohesion, (P_{20}/W) was constant for a greater range of loads and contact pressure."

e. Effect of repetitive traffic. Because of the light test loads, significant changes in wheel performance and soil property values occurred only for the weakest Yuma sand test condition, S_1 (loose, air-dry). For S_1, G increased with pass number and P_{20}/W increased by some 10-20 percent after 10 passes.

f. Slope climbing ability. Tests of the original candidate wheels showed that the Bendix wheel could be expected to propel a vehicle up a slope of about 28 to 30 deg; the Boeing-GM and Grumman, only about 15 to 20 deg. Modifications to the Bendix and Grumman wheels enhanced their performance to the point that they might be expected to climb slopes in excess of 30 deg; the Boeing-GM, about 25 deg.

g. Pneumatic versus metal-elastic wheel. An example of this type comparison was shown under b. Effect of soil strength (cohesion).

h. Prediction of in-soil wheeled vehicle mobility performance from single wheel tests. It was recognized that, even for wheeled vehicles traveling straight-line with successive wheels exactly tracking, in-soil operation of a wheeled vehicle differs from that of multiple passes of single wheels in many important respects, including: slip of successive vehicle wheels at a given point in soil may be different, vehicle load transfer places different loads on successive vehicle wheels (especially during slope ascent and descent and during vehicle acceleration and deceleration); soil failure patterns under vehicle wheel loads differ as slope changes; etc. Nevertheless, it was determined from analysis of test results of the single pneumatic and SLRV wheels and of the surrogate wheeled vehicles (4x4 and 6x6) that estimates of the slope climbing ability of the 4x4 and 6x6 vehicles could be predicted from results of the single-wheel tests (conservative by about 1 to 2 deg). These test results confirmed (approximately) the assumption that P_{20}/W is equivalent to the tangent of the angle of the slope that a vehicle is climbing; thus, P_{20}/W plus the tangent of the angle of the slope being climbed approximates maximum slope climbable. (For comparison with 4x4 and 6x6 test results, test data for corresponding single wheels and loads were averaged for the number of single wheel passes equal to the number of vehicle axles.)

Results from (Green and Melzer, 1970 and 1972). Following award of the Manned Lunar Rover Vehicle (MLRV) system to Boeing-GM, Boeing constructed several modifications of the Boeing-GM wheel with the aim of providing an optimum design for lunar surface performance. WES conducted programmed increasing slip and constant slip tests of six designs of Boeing-GM wheels (X through XV) in LSS_1, LSS_2, LSS_3, and LSS_4. Wheel designs X and XIII, each of approximately the same design and with a metal chevron trend covering 50 percent of its otherwise open-mesh wheel-soil contact surface, performed somewhat better than did the other wheel designs. Soil accumulated in each wheel during a given test, the amount increasing approximately linearly with slip. Less soil accumulated in wheel designs X and XIII than in wheels either with a fully open mesh or with a 75 percent chevron cover. Also, designs X and XIII performed somewhat better than the other wheel designs relative to pull, torque and power performance, as illustrated by averages of first and second pass data from tests in LSS_1 for the following dimensionless performance terms:

Wheels	Percent Cover	P_{20}/W	PN_{SP}	PN_{20}
X and XIII	50	0.30	0.11	0.48
XIV	0	0.22	0.12	0.51
IX	75	0.21	0.19	0.52
XII*	100	0.11	0.18	0.42
XI	100	0.02	0.18	0.23

* With grousers.

Results from (Melzer 1971) and (Melzer and Green, 1971). Two nearly identical Boeing-GM wheels were tested (designs XIII and XV, 50 percent chevron tread, as described earlier for the XIII) in LSS_4 and LSS_5. Major test results included:

a. Effects of wheel speed, acceleration and load. For the range of conditions tested for wheel speed (0.5 to 3.0 m/sec), wheel acceleration (0 to 0.78 m/sec^2) and wheel load (178 to 377 N), in-soil wheel performance (as defined in terms of pull coefficient, power number, and system efficiency] was not affected.

b. Effect of load on wheel sinkage. Wheel sinkage for the self-propelled and 20 percent slip conditions (z_{SP} and z_{20}) appeared to increase linearly with load (but with a maximum z value attained of only about 3.0 cm).

c. Effects of fender and direction of travel. The presence of a fender and the direction of wheel travel each had negligible influence on in-soil wheel performance.

d. Effects of soil strength. Increasing soil strength (as characterized by G, the gradient of the curve of cone index (CI) versus depth of cone penetration) from G = 1.01 MN/m^3 for LSS_4 to G = 6.29 MN/m^3 for LSS_5 caused in-soil wheel performance generally to increase--i.e., for a given level of positive slip, P/W and PN each increased as G increased; for a given value of slope (or P_{20}/W), slip decreased as G increased (causing system efficiency to increase as G increased).

e. Maximum slope climbable. The maximum slope the LRV could climb without using excessive power was calculated to be about 19 deg in LSS_4, about 23 deg in LSS_5.

f. Effect of soil type (Yuma sand versus LSS). (Melzer, 1971 and Melzer and Green, 1971) compared the performance of the essentially identical Boeing-GM wheels obtained in tests in Yuma sand and in LSS_4 of nearly the same strength (G) levels and within comparable ranges of wheel speed. This "snapshot" for three tests of comparable conditions suggested that the wheels performed nearly the same in the two soils, as indicated by the following:

Results from (Green, 1971). From (Freitag, Green and Melzer, May 1970) "On the basis of observations during these tests (of the original candidate wheels in Yuma sand), it is estimated that maximum slope climbable was reduced by 1 to 2 deg when an effort was made to steer the vehicles." (Green, 1971) analyzed the effects of yaw angle on steering forces for the 50 percent chevron-covered Boeing-GM LRV wheel tested in LSS_4 at yaw angles ranging from -5 to +90 deg (plane of wheel perpendicular to its axis of advance), speeds from 1.07 to 3.05 m/sec, loads from 187 to 365 N, and over a programmed range of values of negative slip (positive skid) in the towed or braked-wheel portion of a programmed increasing slip test (i.e., for negative slips up to P = 0 in tests as characterized by Figure 6). Major conclusions reached were:

a. Effects of speed and yaw angle on S_T/W, z_T/d, and P_T/W. For the 0-deg yaw angle, side thrust was negligible, and neither sinkage coefficient z_T/d nor towed force coefficient P_T/W were significantly affected by wheel speed. For yaw angles of 5, 10 and 25 deg, z_T/d and side-thrust coefficient S_T/W each decreased somewhat with speed, with significant separations in the z_T/d versus speed and S_T/W versus speed relations by values of yaw angle. Side thrust, sinkage and skid each increased significantly as yaw angle was increased from -5 to 90 deg (with the curves for these three relations characterized by three d'fferent shapes).

b. Effects of yaw angle on P_T/W. Data scatter obscured the relation of P_T/W to yaw angle for the conditions tested, but P_T/W appeared to decrease slightly as yaw angle was increased above 0 deg.

c. Effects of load and speed. For the range of conditions tested, wheel load had negligible effects on S_T/W, z_T/d, and P_T/W; skid was relatively independent of load and speed, and increased in approximately linear fashion with increasing yaw angle.

Analysis of in-soil performance of concept tracked running gear

Rationale for tracked concept. This rationale was expressed well in (Melzer and Trautwein, 1972), which was prepared after the Boeing-GM wheels had proved successful in MLRV applications on the moon:

> "... in anticipation of future...lunar exploration missions, Lockheed Missiles and Space Company (Lockheed) recently developed an Elastic Loop Mobility System (ELMS) (Figure 11) which combines the major advantages of wheeled vehicles, such as mechanical simplicity, good reliability, and low internal losses, with the advantages of tracked vehicles, such as reduced and more uniform ground contact pressure, resulting in improved soft-soil performance and superior obstacle negotiation."

Versions of ELMS tested. WES conducted mobility tests of initial and improved versions (I and II, respectively) of the prototype scale ELMS. ELMS I and II were each 1.8 m long and 35.6 cm wide. The basic structural component of the ELMS was an elastic loop formed from a continuous strip of high-strength metallic or fiber-reinforced composite material with transverse curvature. The two 180-deg bends in the loop were designed to provide spring suspension for a vehicle supported by the loop, and the lower straight section was intended to distribute vehicle load uniformly over a large footprint area. (Costes and Trautwein, 1972) provides a detailed description of the design and functional characteristics of the ELMS. In addition to the prototype ELMS tests conducted at WES, tests of single- and multi-unit small-scale ELMS models were conducted by the Geotechnical Research Laboratory, George C. Marshall Space Flight Center (MFSC) in Huntsville, Alabama.

Results from (Melzer and Green, 1971) and (Melzer and Trautwein, 1972). The ELMS I was tested in LSS_4 with three types of coverings at the outer ELMS surface (three combinations of grousers and sandpaper strips). Analysis of the test results showed the following:

a. Soft soil performance. For the values of ELMS I speeds tested (0.9, 1.8 and 3.0 m/sec), the level ground, soft-soil performance of ELMS I was influenced by speed--pull developed and energy required decreased substantially as speed increased, while track system efficiency was more-or-less independent of speed. Soft soil performance was not significantly affected by the three ELMS I loop outer surface conditions, and generally improved with increasing number of track passes.

b. Step-obstacle-surmounting and crevasse-crossing performance. The highest rigid, rough-surfaced step obstacle surmounted by the ELMS I was 30 cm high. This type performance varied as a function of both ELMS I outer loop surface condition and obstacle surface condition. The maximum crevasse traversed by the ELMS I was 140 cm wide for the speeds of this study (1.8 to 3.0 m/sec). Crevasse crossing performance was independent of surface conditions of either the ELMS I outer loop or the crevasse.

c. Slope climbing performance. In-soil slope climbable depended on the surface condition of the ELMS I outer loop and on the manner in which the ELMS I was linked to a two-wheeled trailer that simulated a second ELMS I unit. The maximum slope climbed was 30 deg with the trailer mounted so that its attachment to ELMS I allowed free pivoting.

d. ELMS I mechanical shortcomings. Shortcomings in ELMS I that were noted as being improvable concerned limitations relative to torque, internal losses, and ride.

e. Performance of ELMS I versus LRV wheel. Soft soil ELMS I performance closely matched that of the Boeing-GM XIII wheel used for the LRV, as illustrated by the following two-pass average data for the GM XIII and ELMS I each operating at about 0.8 m/sec in LSS_4:

Running Gear	P_T/W	P_{20}/W	PN_{SP}	PN_{20}	N_{20}
GM XIII (for LRV)	0.07	0.36	0.12	0.58	0.63
ELMS I*	0.19	0.33	0.14	0.52	0.61

* Average for three ELMS loop outer surface conditions.

Results from (Melzer and Swanson, 1974). ELMS II, an improved version of ELMS I, was tested in LSS_1 and LSS_5. Some of the major results obtained were:

a. Soft soil performance. ELMS II soft soil performance was independent of test load and translational speed within the ranges of values tested (565 to 690 N and 0.5 to 1.5 m/sec, respectively). Such performance was influenced by soil strength and by the ELMS II pitch mode (i.e., by restrained-versus free-pitch connection of the ELMS II to its connecting trailer). For a given level of output pull, power requirements were smaller for a dense (LSS_5) then for a loose (LSS_1) soil; output pull was larger for the ELMS II operating in restrained-pitch than in free-pitch mode.

b. Step-obstacle-surmounting and crevasse-crossing performance. The highest rigid, rough-surfaced step obstacle surmounted by ELMS II was 46 cm high, and the maximum crevasse crossed was 100 cm wide. Larger obstacles or crevasses could have been negotiated if the ELMS II trailer were replaced by either a second or a system of powered ELMS II units.

c. Slope climbing performance. Slope climbing tests of the ELMS II were conducted with a trailer behind the ELMS to stabilize the single-unit ELMS II. The ELMS II climbed slopes up to 35 deg in LSS_5 in free-pitch mode, 34 deg in restrained-pitch mode. Analysis indicated that if load transfer from the ELMS II to the trailer in restrained-pitch mode could be eliminated (e.g., by replacing the trailer with a second powered ELMS II), then the two-unit ELMS II should be able to climb slopes up to about 38 deg in dense (LSS_5) soil, 35 deg in loose (LSS_1) soil. Slope climbing capability for the ELMS II with or without a second trailer unit (say, a second, powered ELMS II) in either free- or restrained-pitch mode could be estimated from results of tests conducted on level ground. (This type of analytical capability had not been developed earlier in (Melzer and Green, 1971).)

d. ELMS II versus ELMS I mechanical characteristics. ELMS II internal losses were smaller than those of ELMS I for up to about 60 percent of total torque available; for higher torques the reverse was true. Contact pressures were more uniform for ELMS II than for ELMS I. Along the longitudinal axis of the ELMS II loop maximum contact pressure occurred toward the middle of the loop, whereas along the transverse axis maximum pressure occurred at the loop edges.

e. Performance of ELMS II versus ELMS I and LRV wheel. Overall, the ELMS II provided performance significantly superior to that of either the ELMS I or the LRV wheel, as illustrated, for example, by Figure 12.

Results from Costes, Melzer and Trautwein, 1973. This paper described major findings from mobility tests conducted along straight-line paths on level and inclined smooth surfaces of LSS (a) by WES using the prototype-scale ELMS II, and (b) by MFSC using single and several multi-unit, small-scale ELMS models. Among the major findings were the following:

a. Relation of prototype-scale to model-scale ELMS. Close agreement was determined between performance achieved by the prototype-scale ELMS II and the small-scale ELMS models, as evidenced, for example, by comparisons made for relations of slope angle negotiated-versus-slip and PN-versus-P/W at comparable conditions of soil strength, pitch mode and grouser spacing.

b. Maximum slope climbing capability. This capability of the single prototype scale ELMS and the single LRV wheel was evaluated for comparable conditions of load, soil strength, and speed on the basis of values of maximum slope climbable as estimated from P/W values measured in tests on level LSS. Results in Figure 13 show that the single ELMS track far outperformed the single LRV wheels in all three ELMS pitch modes evaluated, but particularly with pitch restrained.

c. Obstacle-surmounting and crevasse-crossing capabilities. Capabilities of the single ELMS far exceeded those of the single LRV wheels, illustrated as follows:

Running Gear	Pitch Condition	Maximum Step Obstacle Climbed (cm)	Maximum Crevasse Crossed (cm)
LRV wheels	-	30	70
ELMS	Free	46	>100
ELMS	Restrained	38	>100

Results of tests with the ELMS 3x3 vehicle models indicated that ELMS obstacle-climbing and crevasse-crossing capabilities (as well as peak torque requirements during obstacle negotiation) were superior to those of known wheeled LRV concepts of comparable vehicle stowed size.

d. Ride quality. Tests of the ELMS over random, rough surfaces indicated that the large footprint and suspension characteristics of the ELMS elastic loop provided ride quality substantially smoother than that of the wheeled rover vehicles studied.

e. Overall mobility and efficiency performance. For the ELMS II, these were determined to be comparable to those of the wheeled LRV for vehicle operation under favorable terrain conditions (firm soil, small slopes) and much superior to the LRV under adverse conditions (loose soil, steep slopes). (See, for example, Figure 12 herein.) These advantages were attributed to the ELMS II large footprint (used to best advantage under restrained-pitch mode), favorable suspension characteristics, and low energy losses.

Lunar Surface Mobility Studies--Some Keys for Future Success

Introduction

From (Melzer and Swanson 1974): "Surface mobility of advanced-design roving vehicles will be the key to future lunar and planetary missions extended over large areas." To assure that the U.S. holds this key, it is important to assess capabilities either available today or achievable in the near future that can be used to define U.S. LRVs capable of moving on and working the surface of the moon.

Some Present Capabilities

Dimensional analysis (numerics). (Turnage, 1972) and (Turnage, 1976) include descriptions of the in-soil mobility performance of a broad range of single pneumatic tires* and several relatively large single model tracks, respectively, developed from dimensional analysis and extensive laboratory testing in air-dry Yuma sand. Typically, single-tire or model-track in-sand performance was described by means of dimensionless performance terms (P/W, z/d, M/Wr_e, etc.) versus dimensionless tire-soil or track-soil prediction terms, or numerics (such as previously described N_{PY} and N_{WY}, for example). (Turnage, 1972) and (Turnage, 1976) describe means for extrapolating dimensionless relations descriptive of single-tire or single-track in-sand mobility performance, respectively, to predict the in-sand performance of full-size vehicles.

As mentioned previously, the Apollo-era studies by WES and by MFSC focused on "snapshot" evaluations of the influences on in-soil wheel or track mobility performance of a number of variables evaluated one by one, as values of other important variables within the wheel-soil or track-soil system were systematically controlled (either held constant or varied within selected limits). This approach provided results which contributed to the definition of a wheeled LRV that operated successfully on the moon. Nevertheless, the authors consider that the "continuum" approach provided by using numerics produces a much more structured and understandable picture not only of (a) the influence on in-soil wheel or track performance of a given variable per se, but also of (b) the range of wheel-soil or track-soil conditions for which that variable's influence applies.

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* Two sizes of solid metal wheels were also tested.

Some benefits of the numeric "continuum" approach can be illustrated relative to three key issues addressed in "snapshot" fashion during the Apollo-era WES studies, as follows:

a. Comparison of single wheel performance in Yuma sand and in LSS. Little examination was made during the Apollo-era WES mobility studies of how closely wheel test results compared for Yuma sand and for LSS. Figure 14 shows the relation of P_{20}/W versus N_{WY} for similar versions of the Boeing-GM wheel (versions I, X, XIII and XV, each having open mesh construction with 50 percent chevron cover) based on tests in Yuma sand and in LSS. (This version Boeing-GM wheel was the only one tested in both Yuma sand and LSS during the WES Apollo-era mobility investigations.) Conditions of Yuma sand (closed data points) included among the data in Figure 14 are S_1 and C_2; conditions of LSS (open data points) are LSS_1, LSS_2, LSS_4 and LSS_5. In Figure 14 the close fit of the test data to a single curve illustrates that the Yuma sand and LSS test conditions used for the Apollo-era WES mobility investigations caused the wheels to produce quantitatively very similar mobility performance results.

b. Prediction of in-soil wheeled vehicle mobility performance from single-wheel tests. As noted previously, several factors that influence the in-soil performance of a wheeled vehicle behave differently during multiple pass tests of single wheels of the same sizes and loads. Nevertheless, for many conditions in-soil wheeled vehicle performance can be accurately predicted from in-soil single-wheel test data. For example, Figure 15a shows the P_{20}/W versus N_{WY} relation based on averaging P_{20}/W values for two passes of the single pneumatic wheel, three passes of the single SLRV. All G values used in Figure 15 were pretest values. The reasonably close fit of all the test data in Figure 15 to the same curve suggests that (a) the pneumatic and SLRV wheels performed about the same, and more importantly (b) some aspects of in-sand wheeled vehicle performance (level ground P_{20}/W, among others) can be accurately predicted from in-sand single-wheel test results.

c. Representation of in-soil running gear mobility performance for a range of conditions. As illustrated in many instances herein, a "snapshot" description is limiting in that it provides to the analyst neither (a) a "feel" for the location of a given data point within the range of running gear-soil conditions practical for the analysis at hand, nor (b) a ready means for extrapolating running gear performance results from one test condition to another. The proper use of numerics removes these limitations. For example, relative to the analysis of tests in Yuma sand of the candidate wheels for the LRV, the curve in Figure 16a was defined for values of N_{WY} up to about 1500 from the results of single-wheel tests of various pneumatic tires and two solid metal wheels tested over broad ranges of values of each variable included in N_{WY}--values of sand penetration resistance gradient (G) from 2.3 to 27.7 MN/m^3, wheel width (b) from 4.3 to 41.1 cm, diameter (d) from 35.6 to 104.8 cm, tire shape factor (b/d) from 0.06 to 0.90, load (W) from 191 to 20,020N, and deflection ratio ($2\delta/d$) from 0 to 0.22. That part of the curve in Figure 16a for values of N_{WY} greater than 1500 was defined by the open-symbol data points (results of tests of the single pneumatic wheel by WES during the LRV program). The overall curve in Figure 16a can be considered a datum for comparing the P_{20}/W performance levels of the several single candidate wheels for the LRV; those performances are depicted as faired dash or dot-dash lines in Figures 16a through 16d. Those figures illustrate that the P_{20}/W performances of the Bendix, Boeing-GM, Grumman and SLRV wheels can readily be compared to that of the pneumatic wheel or be compared among themselves for any selected value or range of values of N_{WY}.

Important among the characteristics of the relations between properly formulated dimensionless performance terms (e.g., P_{20}/W) and numerics (e.g., N_{WY}) are the following: (a) for each distinctive type of wheel construction (say, bias ply pneumatic or SLRV or Bendix I or...) a particular dimensionless performance term versus numeric relation exists, nearly always in the form of a "continuum"; this relation may or may not be the same as for other types of wheeled construction (or even for modifications of the same type construction); (b) a particular dimensionless performance term versus numeric relation can be applied at least within the full range of values of parameters in the numeric whose test results were used in defining that relation (and usually well beyond that range);and (c) a given value of a numeric (e.g., N_{WY}) is properly described by any combination of values of the individual parameters within the numeric (e.g., G, b, d, W, and δ in N_{WY}) that produces that particular value, within the constraints described in (b). Thus, the same value of N_{WY} is defined for b and W as for 2b and 2W, for example, with that particular N_{WY} value corresponding to a single value of P_{20}/W. This powerful property enables results from a relatively few wheel-soil tests to be generalized to a very broad range of wheel-soil conditions.

Computerized models (AMM and Push-It). A major breakthrough in vehicle mobility prediction capability was achieved near the end of the Apollo-era mobility investigations when the first version of the comprehensive, computerized Army Mobility Model (AMM) was produced in 1971 (Staffs of WES and TACOM, 1971). Developed primarily for military applications, AMM is backed by nearly 50 years of WES experience in vehicle mobility field testing and analytical mobility modeling. AMM requires a detailed input description of those terrain, vehicle, driver, weather and scenario (mission) parameters which have most influence on terrestrial on- and off-road vehicle mobility. For terrestrial terrain, AMM uses input values for a number of individual factors to describe off-road areal terrain (broad land features), off-road linear features (streams, long gaps and mounds), and on-road terrain (road and trail networks). Wheeled and tracked vehicles are described in AMM by factors that define a given vehicle's geometry (size and shape), inertial characteristics (weight and weight distribution), and mechanical attributes (drive train, suspension, etc.). Drivers are described in AMM in terms of their capabilities as vehicle operators to avoid obstacles to travel (recognition distance and reaction time), and to withstand vibrations and jolts (due to ground surface microroughness and sizeable discrete obstacles, respectively). Weather is described primarily relative to type (rain, snow, fog, etc.) and precipitation accumulation. And scenario factors in AMM define locations of journey start and finish, plus ground rules for vehicle travel between these locations.

AMM describes quantitatively a given vehicle's capability to travel unassisted between essentially any given terrestrial points A and B. Obviously, not all of AMM's mobility prediction capabilities are applicable to lunar surface vehicle travel--the moon has no roads or wet gaps, for instance. However, AMM does predict vehicle mobility relative to essentially all types of resistances to vehicle travel that are anticipated on the moon's surface--soft soil, slopes, surface microroughness, discrete obstacles, and dry gaps.

It is emphasized that AMM's present capabilities do not provide a panacea for predicting lunar surface mobility. AMM can now be used to accurately predict terrestrial surface mobility for existent and proposed (paper) vehicles, but only for vehicles that, by today's standards, are reasonably conventional--i.e., only for pneumatic-tired vehicles and for conventionally tracked vehicles whose geometric, inertial and mechanical characteristics are not radically different from current vehicle designs. Experience from the Apollo-era wheel and track studies indicates that running gear and vehicle designs that are radically different from today's standards likely will be proposed for future U.S. travel on the lunar surface. That experience further indicates that some of those novel designs (e.g., the ELMS) will perform extraordinarily well on the moon. AMM software provides an excellent starting point from which to model the lunar surface mobility capabilities of essentially any running gear or vehicle design; depending on the particular design involved, necessary modifications to AMM can range from minor to major.

A WES computerized model developed to describe bulldozer grading capabilities for terrestrial applications (Rush and Willoughby, 1972), now sometimes referred to as the "Push-It Model," can be used in association with AMM to describe terrestrial bulldozer work rates and associated mobility capabilities. Modifying Push-It to describe bulldozer performance in the lunar environment could require effort ranging from minor to major, depending on how novel the design of the lunar bulldozer involved.

Some Lessons Learned from Apollo

Lunar soil simulation. It should not be necessary either (a) to conduct again the exhaustive battery of soil laboratory tests used during the Apollo era to identify and quantify soil characteristics important to lunar vehicle mobility, or (b) to relearn how to simulate those characteristics with terrestrial soils, or (c) to decide the best parameters to use for characterizing major physical characteristics of terrestrial LSS. The lunar soil characteristics most important to simulate are those included in Figures 1, 2, 3 and 4 herein, particularly those in Figures 1 and 4. Trenching tests and cone penetration resistance tests should be among soil tests conducted in future lunar expeditions; information from these two types of tests should be used to augment information from corresponding tests conducted during the Apollo era. To provide an LSS suitable for mobility studies, either Yuma sand or basalt processed as in the Apollo-era mobility studies should be acceptable. Finally, the strength and uniformity characteristics of a given LSS test section should be described in terms of penetration resistance gradient, G (augmented primarily by measurements of w, D_r and ρ_d).

Physical testing. As was made clear during Apollo-era laboratory tests of both the several candidate wheels for the LRV and the two versions of ELMS, modifications to a given basic design of vehicle running gear (e.g., adding grousers, roughening the soil contact surface, changing the suspension characteristics, etc.) can change the in-soil mobility performance of that running gear, sometimes drastically. Thus, particularly when novel designs of running gear are involved, it is imperative to physically test each design in LSS to determine the particular mobility capabilities of that design.

Summation

Aided by dimensional analysis (e.g., the judicious use of soil-running gear numerics) and by computerized vehicle mobility and soil-working models (e.g., application of lunar-modified AMM and Push-It models, respectively), together with lessons learned from Apollo (e.g., identification of Yuma sand or basalt as a useful LSS, and recognition of the necessity to physically test proposed LRV concepts), the United States is in far better position today than twenty years ago to develop outstanding capabilities for traveling on and working the surface of the moon. With national will, this objective can be achieved.

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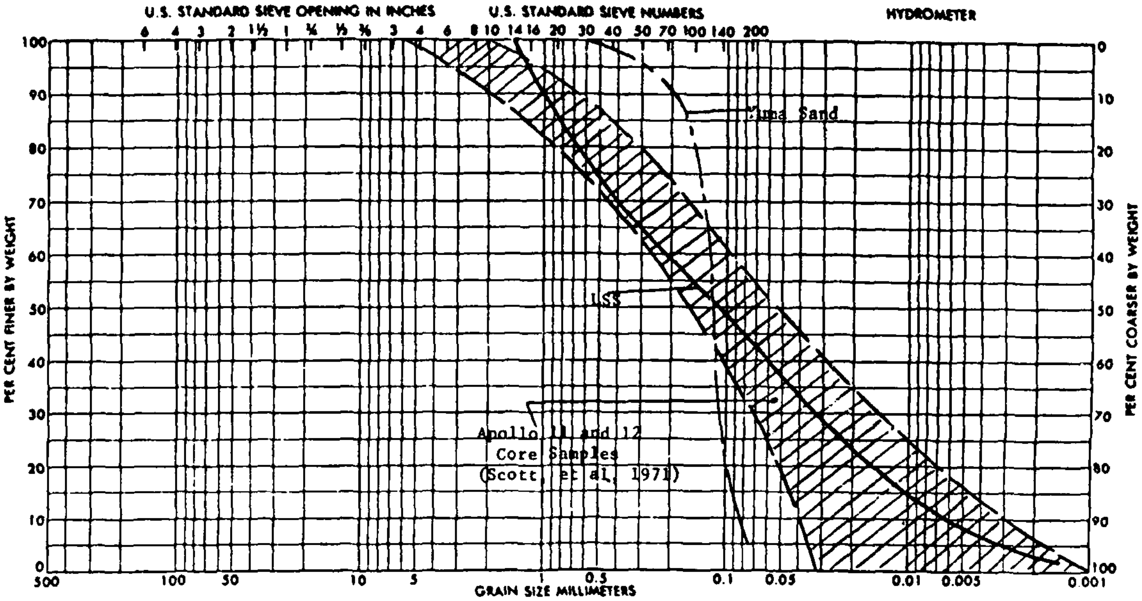
Abbreviations

A_c	Contact area of a wheel measured under load on a hard, flat surface, sq cm
AMM	Army Mobility Model
b	Wheel width, cm
c	Cohesion, kPa
c_a	Apparent cohesion, kPa
CI	Cone index, kPa
CW_{max}	Maximum crevasse width negotiable, cm
d	Wheel diameter, cm
D_r	Relative density, percent
ELMS	Elastic Loop Mobility System
G	Soil penetration resistance gradient, MPa/m^3
h	Wheel (pneumatic tire) section height, cm
ℓ	Hard surface contact length of a tracked running gear, cm
LRV	Lunar Roving Vehicle
LSS	Lunar soil simulant
M	Input torque, M-N
N_{PY}	Numeric for predicting pneumatic tire performance in Yuma sand
N_{WY}	Numeric for predicting wheel performance in Yuma sand
OH_{max}	Maximum obstacle height negotiable, cm
P	Wheel or track pull, N
PCR	Power consumption rate, watt hr/km
PN	Power number
q_c	Cone penetration resistance, kPa
r_e	Effective wheel (or track) radius, cm
s	Slip, expressed as a decimal (not a percent)

S	Side thrust, N
SP	Self-propelled point or condition
T	Towed point or condition
20	Twenty percent slip condition (used as a subscript)
w	Moisture content, percent
W	Wheel (or track) load, N
z	Wheel (or track) sinkage, cm
α	Equivalent slope angle, deg
δ	Deflection of a wheel (or track), cm
ϕ	Angle of soil internal friction, deg
ρ_d	Soil dry density, g/cm^3
σ	Soil confining pressure, kPa
ϕ_{max}	Maximum slope climbable, deg



	C_u	d_{50}, mm	e_{max}	e_{min}	D'	γ_s, g/cm^3
LSS	33.00	0.11	1.116	0.360	2.10	2.85
Yuma sand	1.5	0.12	0.919	0.608	0.51	2.67

Figure 1. Gradation and classification data for LSS and for Yuma sand, approximate gradation band for Apollo 11 and 12 lunar soil core samples (from Melzer 1971).

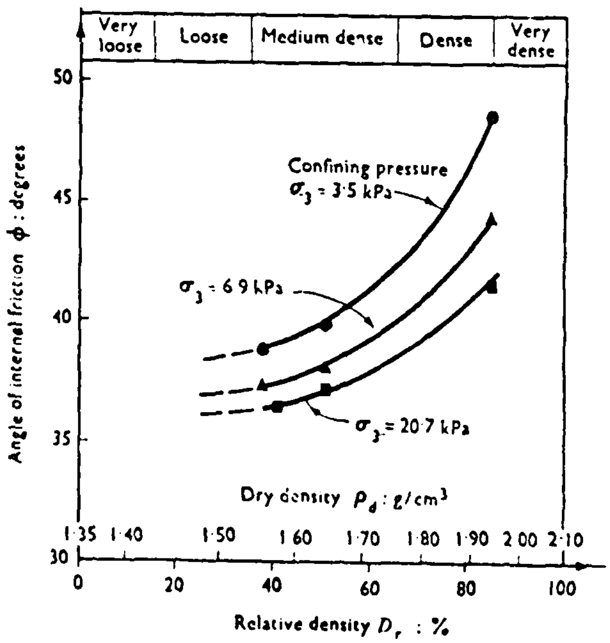


Figure 2. Relations among angle of internal friction ϕ, relative density D_r, dry density ρ_d, and confining pressure from vacuum triaxial tests of LSS (from Melzer 1974).

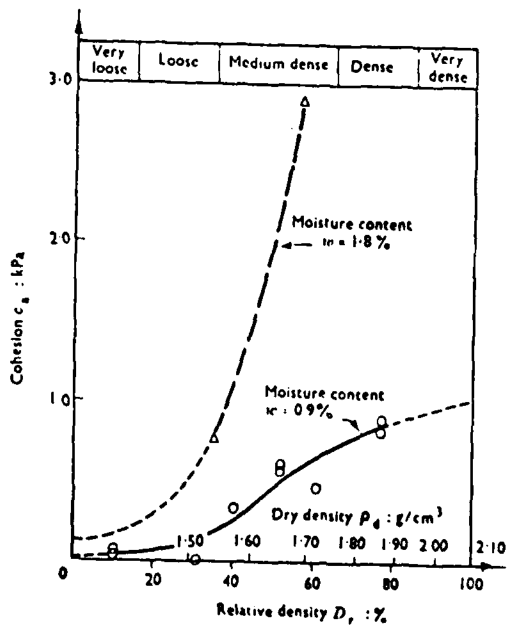


Figure 3. Relations among cohesion c, relative density D_r, dry density ρ_d, and moisture content w from trenching tests of LSS (from Melzer 1974).

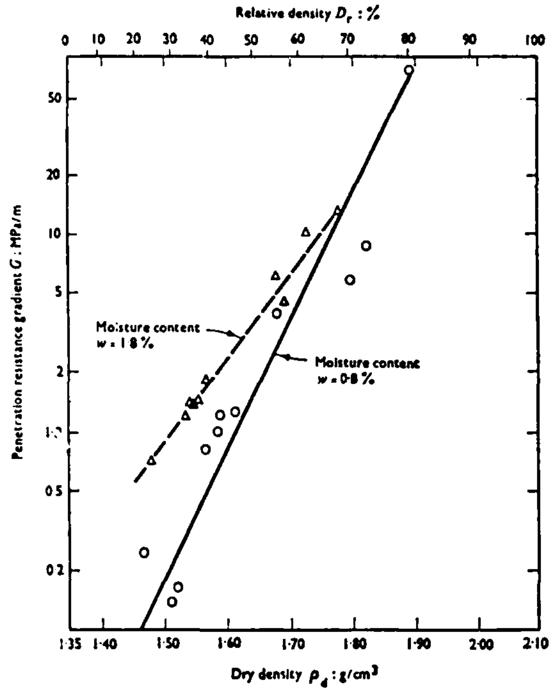
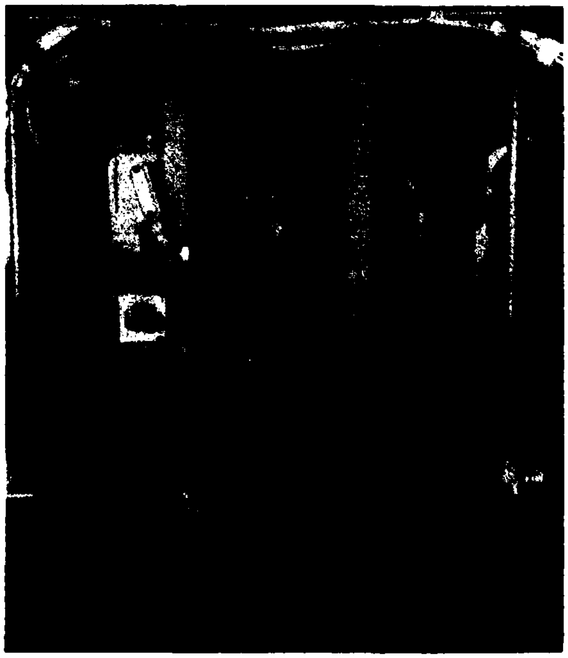


Figure 4. Relations among cone penetration resistance gradient G, dry density ρ_d, relative density D_r, and moisture content w from cone penetration tests of LSS (from Melzer 1974).

Figure 5. WES cone penetrometer in position over soil bin (from Melzer 1974).



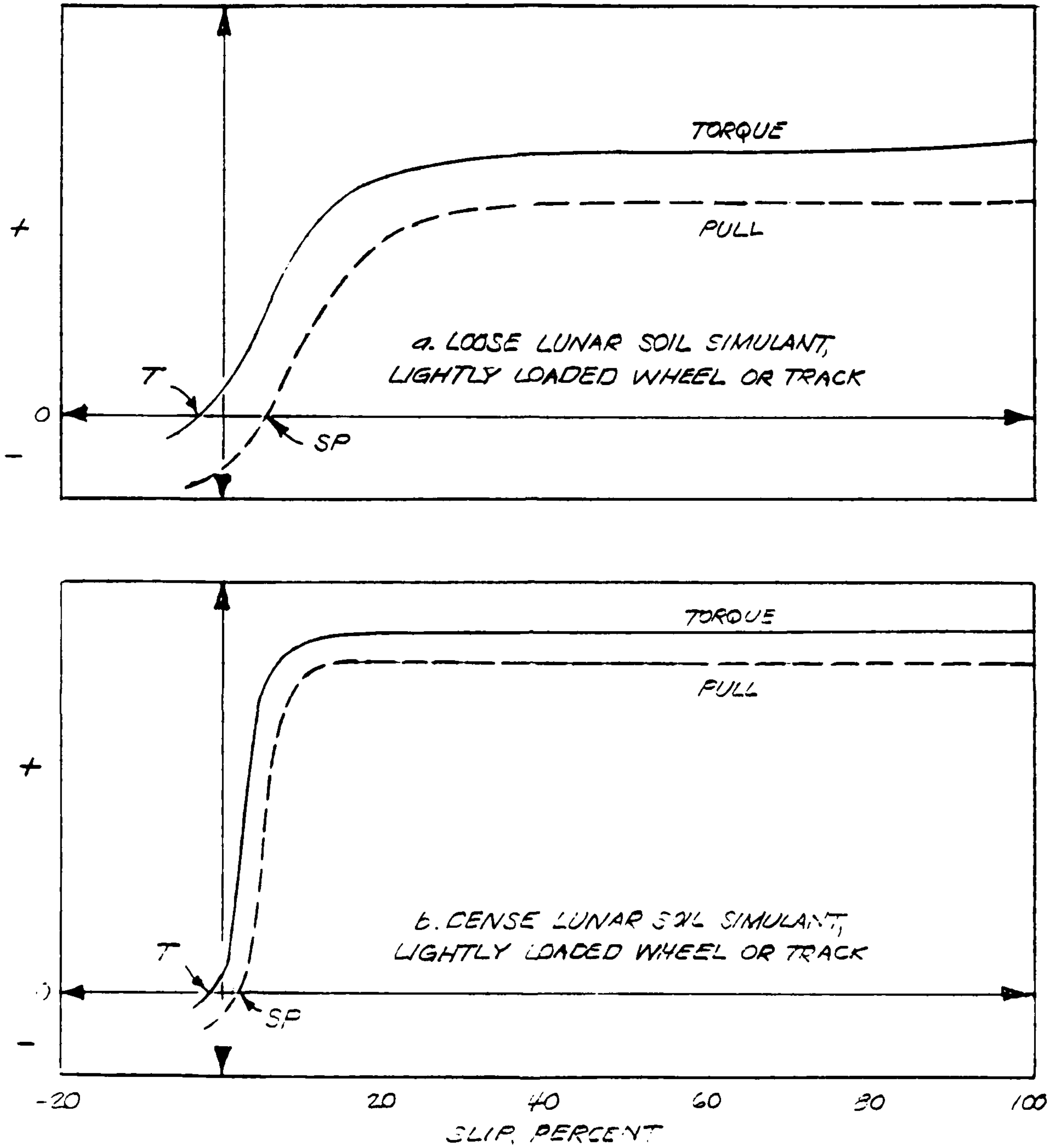
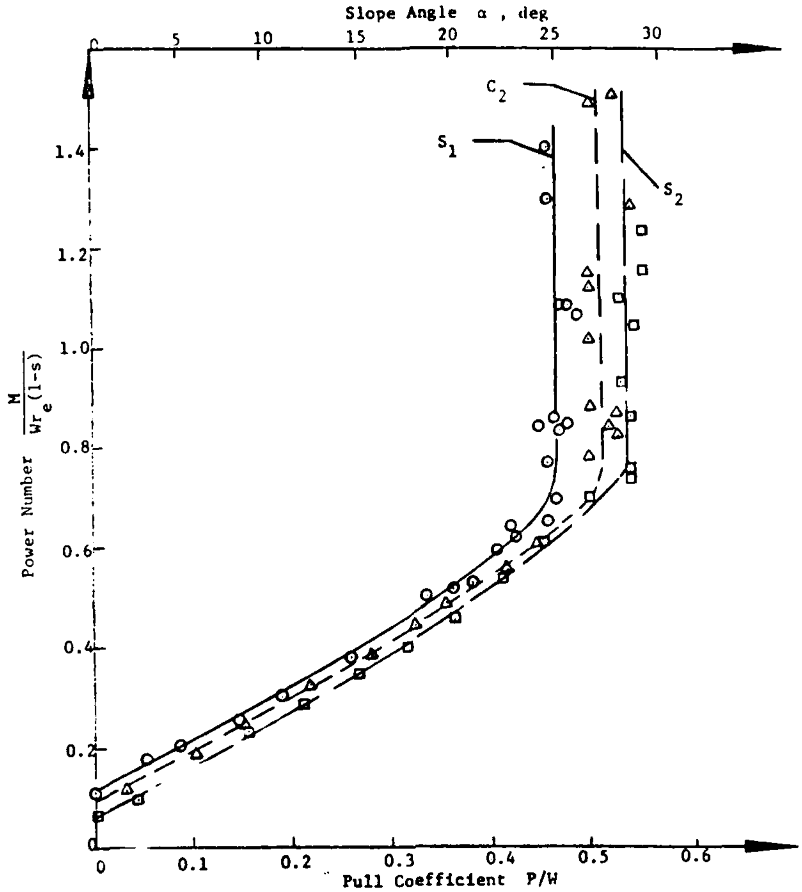


Figure 6. Representative curve shapes for input torque M and output pull P versus slip from programmed increasing slip tests for lightly loaded wheels and tracks in loose and dense lunar soil simulant.



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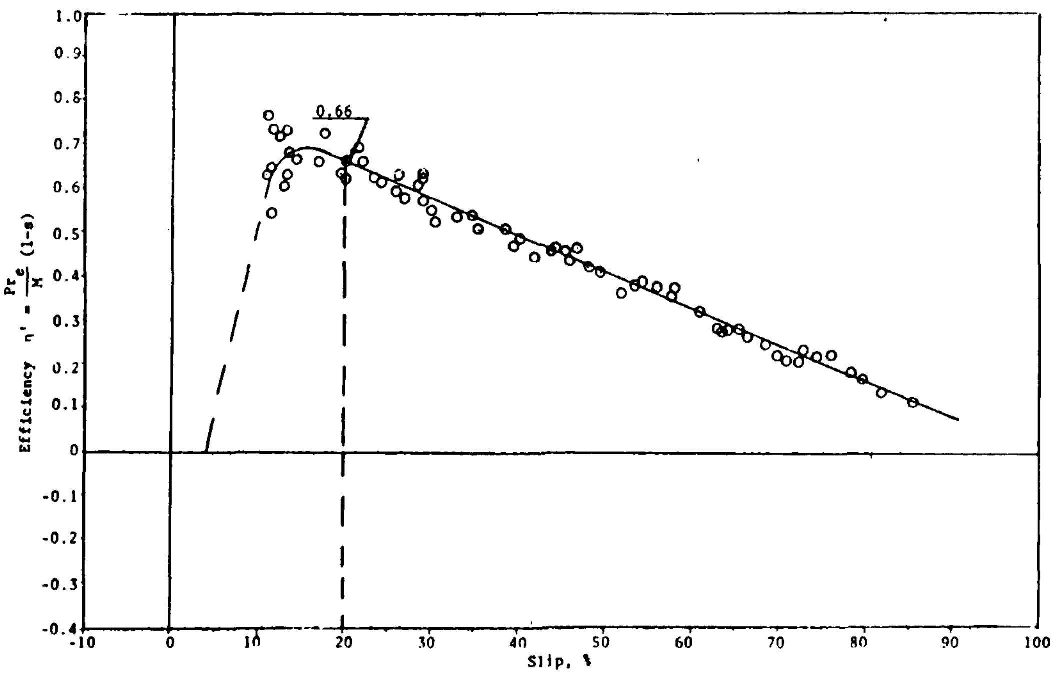


7b

Figure 7. Representative relations of (a) power number to pull coefficient and (b) efficiency to slip for wheel tests in lunar soil simulant (from Freitag, Green and Melzer, May 1970).

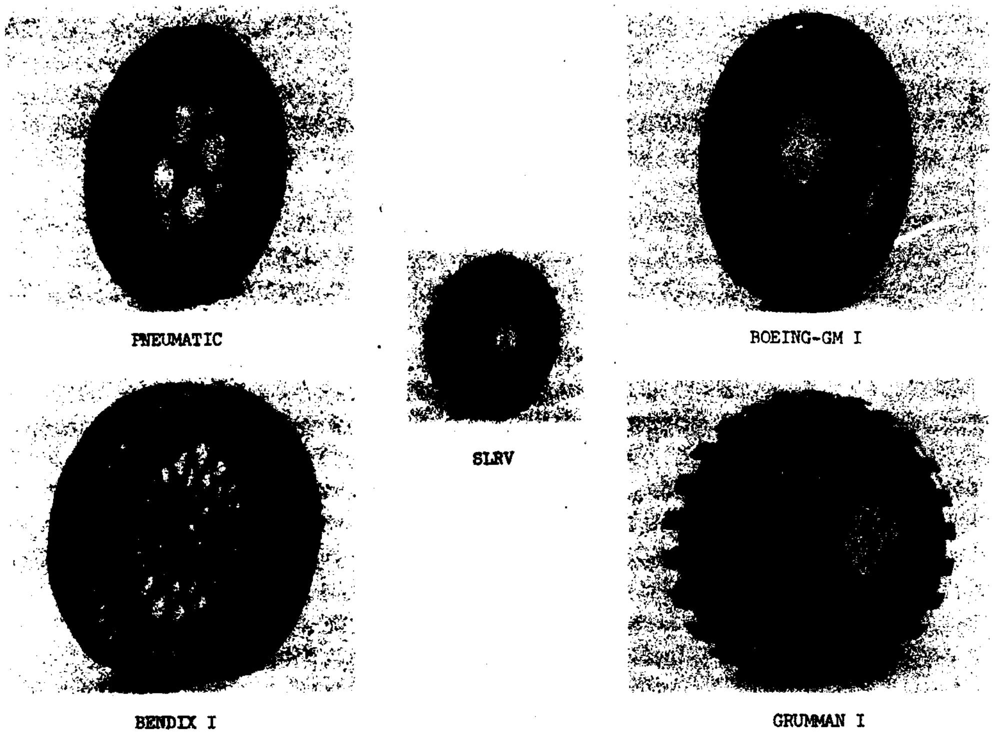


Figure 8. Original wheels evaluated by WES for NASA during Apollo-era mobility test program (from Freitag, Green and Melzer, 1970).

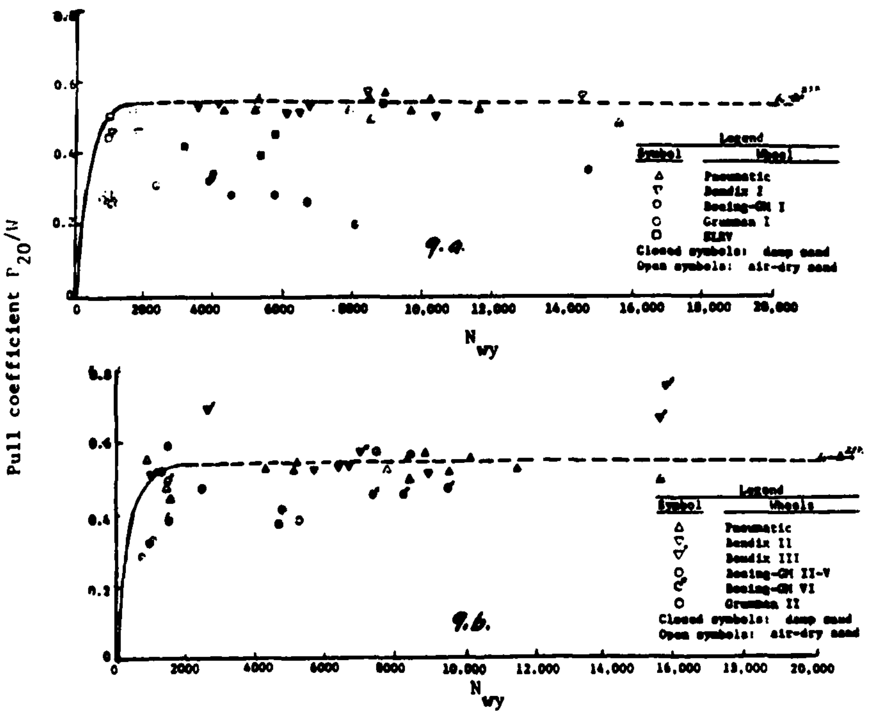


Figure 9. Relations of pull coefficient P_{20}/W versus prediction numeric N_{wy} from WES tests in Yuma sand of (a) the original and (b) the modified LRV candidate wheels (from Freitag, Green and Melzer, March 1970).

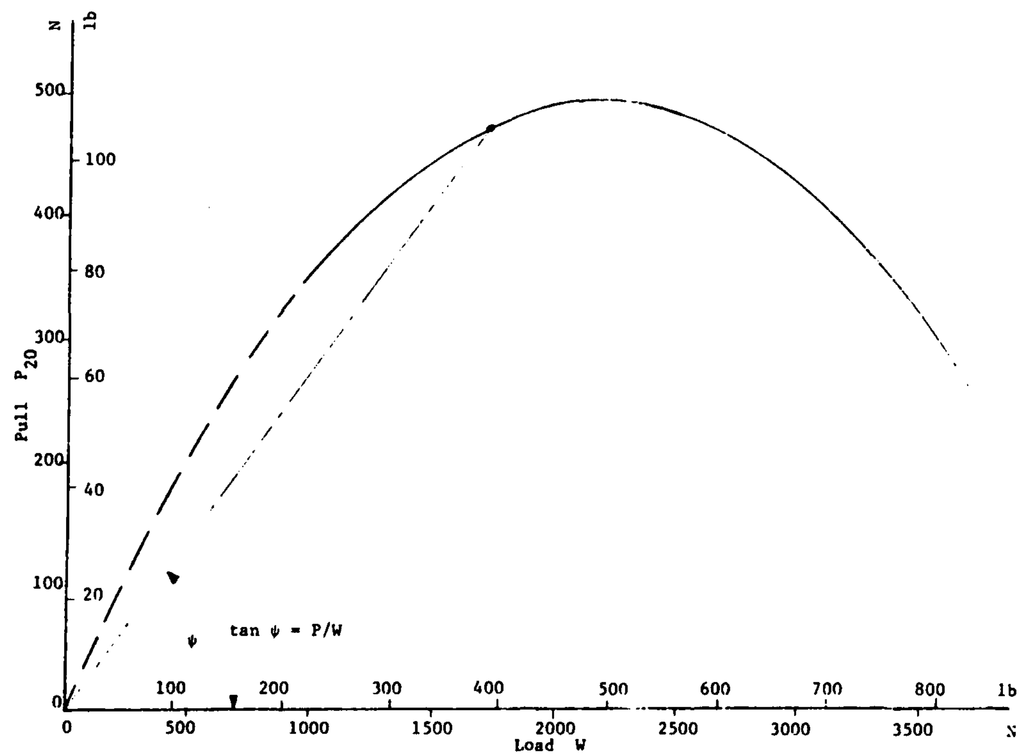
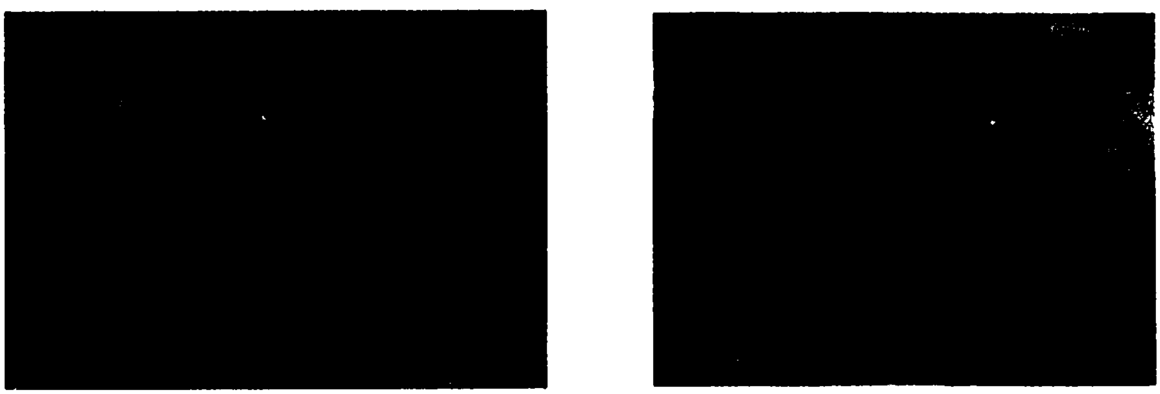


Figure 10. Relation of pull at 20 percent slip to load for a heavily loaded pneumatic wheel on dense, air-dry Yuma sand (from Freitag, Green and Melzer, March 1970).



11a 11b

Figure 11. a. Large-scale single ELMS unit with on-board instrumentation mounted on dynamometer carriage for tests on level LSS, b. Large-scale, self-propelled single ELMS unit with on-board instrumentation and telemetry system, mounted on trailer for tests on LSS slopes under restrained-pitch mode (from Costes, Melzer and Trautwein, 1973).

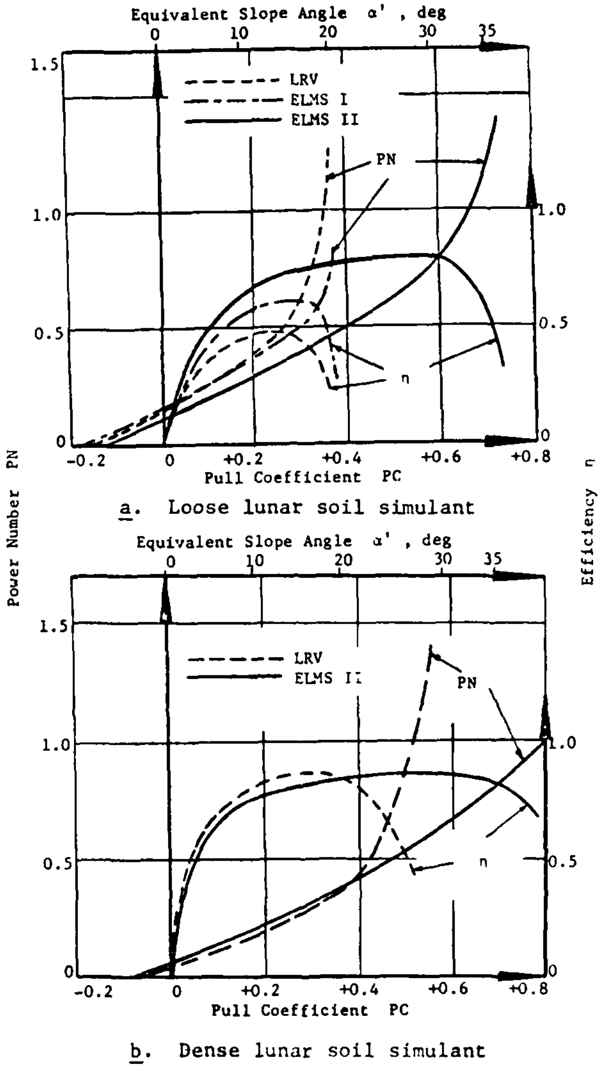


Figure 12. Comparison of performance on level LSS of ELMS II versus ELMS I and LRV wheel (from Melzer and Swanson, 1974).

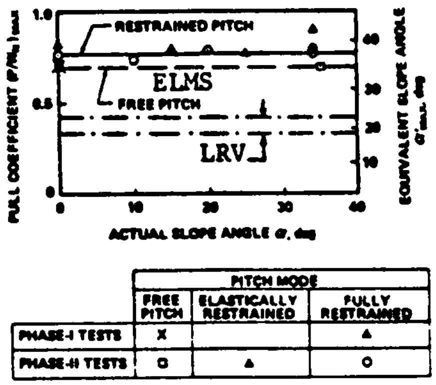


Figure 13. Comparison of pull coefficient and maximum slope climbing capabilities of ELMS II versus ELMS I and LRV wheel, as indicated from tests on level ground and on slopes (from Costes, Melzer and Trautwein, 1973).

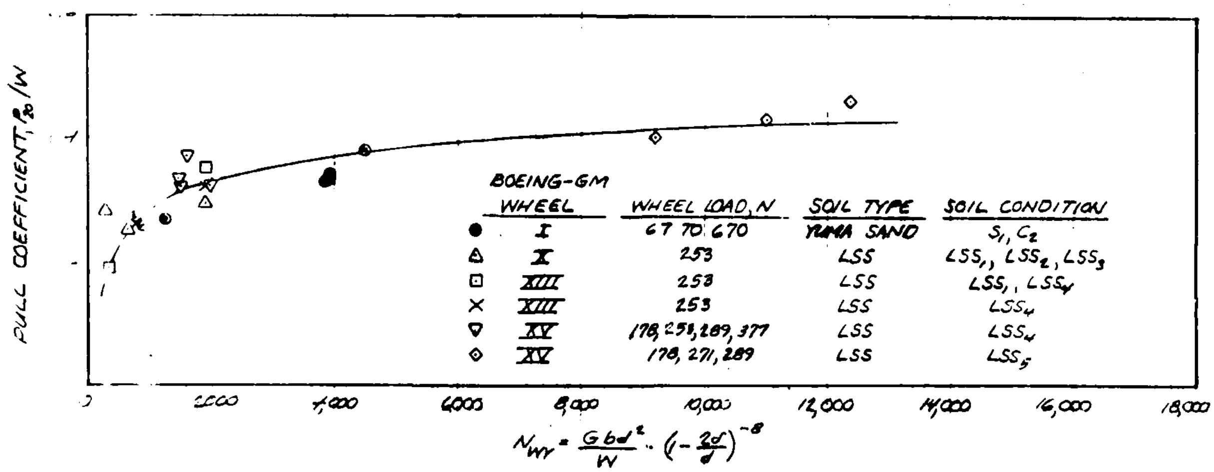


Figure 14. Closeness of test data fit to a single P_{20}/W versus N_{WY} relation for similar Boeing-GM wheels (four versions) tested over a range of light wheel loads and soil conditions in Yuma sand and in LSS.

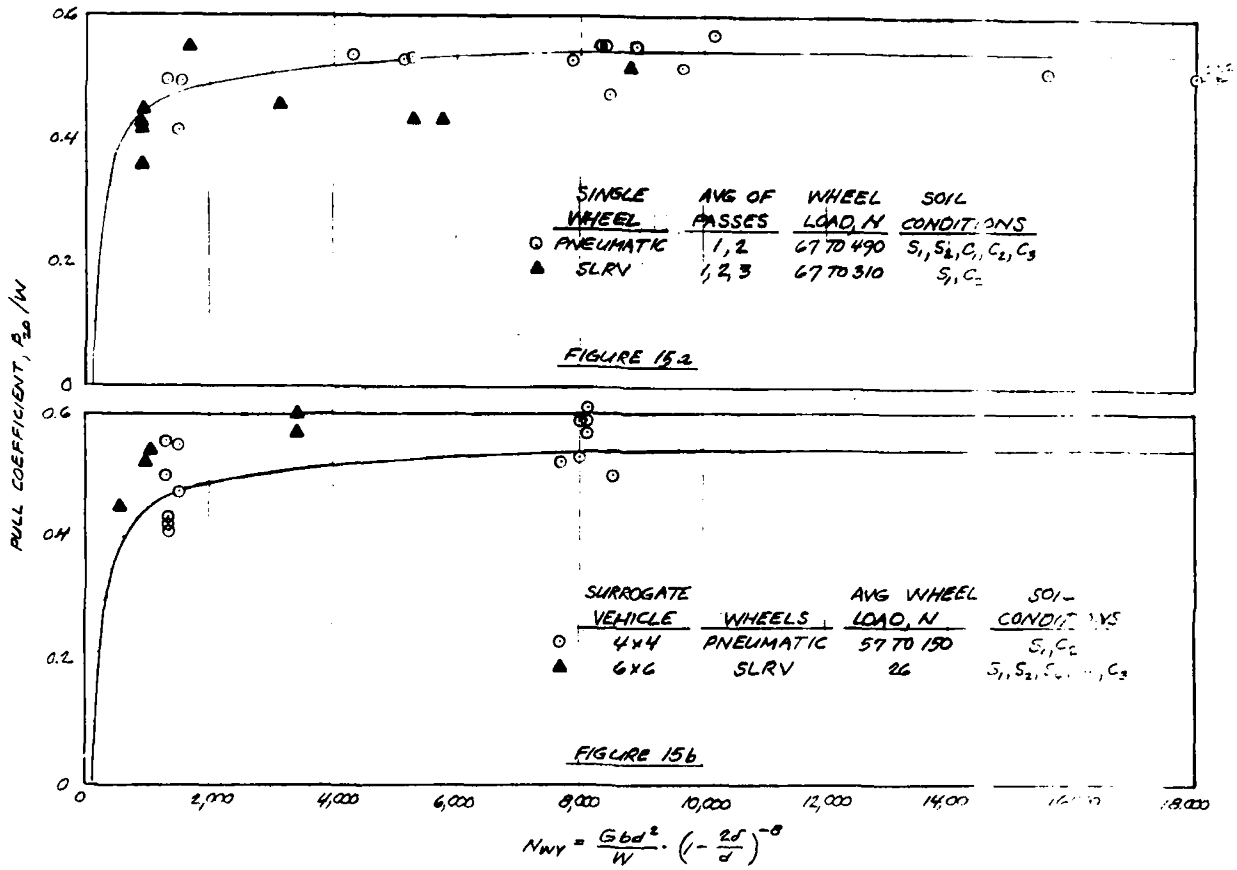


Figure 15. Closeness of data fit to a single P_{20}/W versus N_{wy} relation for (a) average of multi-pass single-wheel tests and (b) one pass of 4x4 and 6x6 surrogate wheeled vehicles (with corresponding wheel sizes, similar ranges of light single-wheel loads, and broad ranges of soil conditions in Yuma sand).

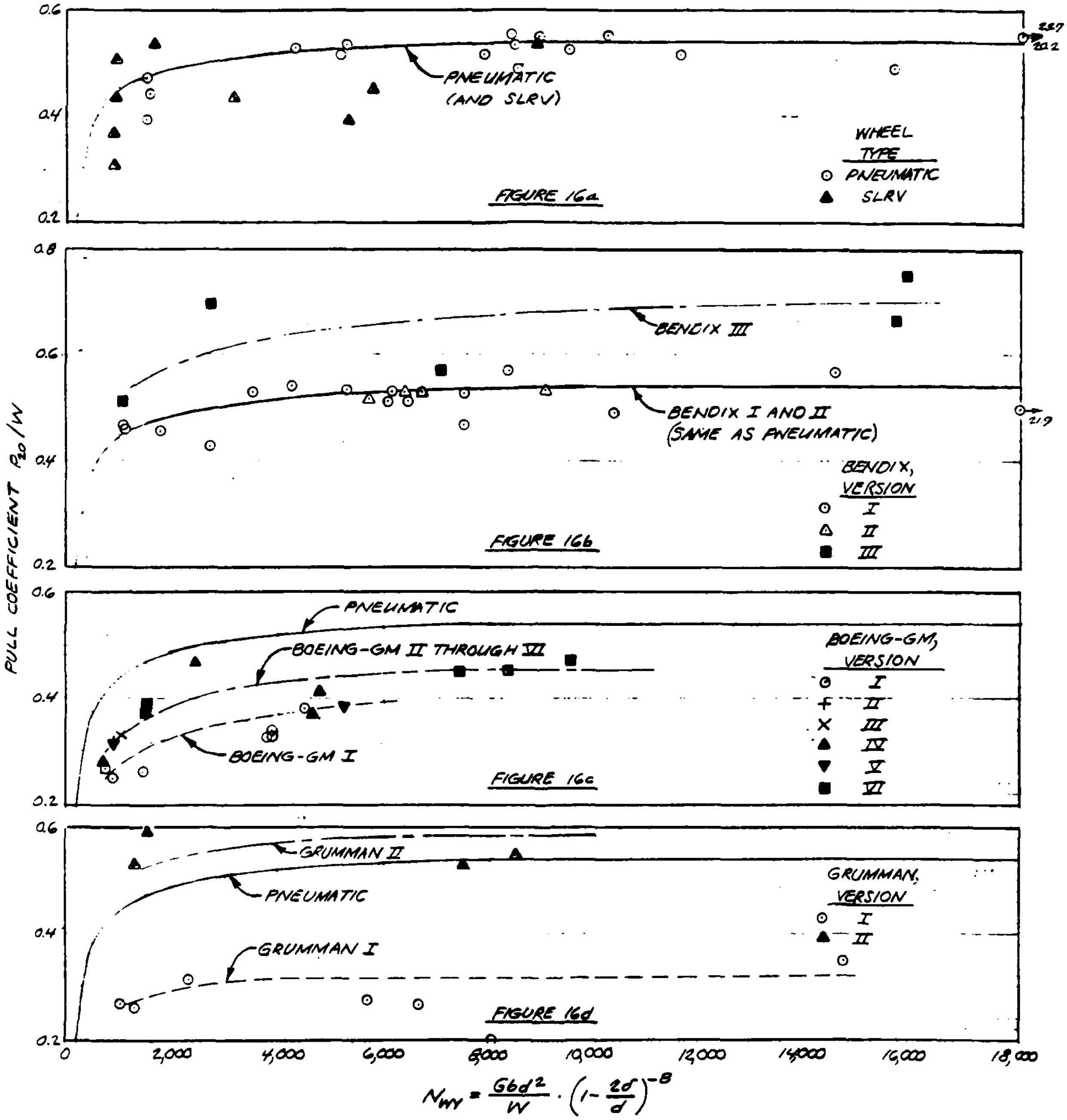


Figure 16. Relations of P_{20}/W versus N_{WY} for tests of Bendix, Boeing-GM, Grumman, pneumatic and SLRV single wheels in Yuma sand (for a range of light wheel loads and soil strength conditions).